TEST METHODS FOR MEASURING FLUID TRANSPORT IN COVER CONCRETE

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ABSTRACT

Four tests for measuring the surface properties of concrete have been studied :the Initial Surface Absorption Test (ISAT), the Figg Air Permeation Index Test (Figg), the Cover Concrete Absorption Test (CAT) and the Air Permeability of the Near Surface (APNS) test. Analytical models are presented for each of the tests to relate the results to fundamental properties of the concrete. Experimental results are presented for the application of a vacuum technique for preconditioning concrete in-situ prior to the Figg and CAT tests. The application of vacuum using ISAT cap did not lead to satisfactory results with these tests. However, direct application of vacuum to the Figg and CAT heads prior to testing resulted in improvement of the reproducibility of the permeation indices obtained from these tests. The analytical models were then used in combination with the experimental results to draw conclusions about the choice of test method for practical applications.

Keywords: Concrete, Durability, Investigation, Permeability, Absorption, Cover.

INTRODUCTION

The damage to cover concrete in existing structures usually involves movement of aggressive fluids from the surrounding environment into the concrete followed by physical and/or chemical actions leading to irreversible deterioration. Therefore the in-situ assessment of permeation characteristics of cover concrete is important for the assessment of durability.

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A great number of permeation tests are available in the literature. These tests can be used for quality control and compliance testing, during and immediately after construction, or to check the residual durability of existing structures (Bungey 1989). This paper presents analytical solutions for four tests which are shown in Table 1.

The major problem which limits the application of these tests in-situ is their sensitivity to the moisture condition of the test concrete. Therefore, the moisture condition of the concrete has to be determined or set to a predefined standard prior to testing. A new technique for preconditioning concrete, both in-situ and in the laboratory prior to testing, was developed by the authors (Dhir et al. 1993). It is based on applying vacuum to a modified ISAT cap and monitoring the progress of drying using silica gel indicator. It was successfully reproducible when tested with the ISAT.

This paper presents theoretical models for the four tests and reports the results of the application of the vacuum drying system to the drilled hole tests (CAT and Figg). The ultimate aim was to improve the application of these tests in-situ (i.e. the reliability and reproducibility of results). The results are used to give guidance on the most appropriate test to use in practical applications.

BACKGROUND TO THE COVERCRETE PERMEATION TESTS

Figg Air Permeation Index

Figg (1973) developed a test for air and water permeability which involved a hole drilled into the concrete surface. Figg's air permeability test method is based on applying low pressure to the drilled hole in the concrete through a hypodermic needle using a hand generated vacuum. In order to improve the repeatability, Cather et al (1984) modified the dimensions of the hole. Further modifications of the test cavity dimensions and the applied pressure level were made by Dhir et al

(1987), which resulted in a reduction of variation from 27 % to 11 %. This version was used in the investigation and is described below.

A test hole of 50 mm depth and 13 mm diameter was drilled into the concrete. After thorough cleaning, the hole was plugged to a depth of 20 mm from the outside surface by polyether foam and then sealed with a catalysed silicon rubber. When the rubber had hardened, a hypodermic needle was pushed through the silicon rubber plug (Figure 1). Connections were then made to the hypodermic needle, to introduce air under vacuum using a hand-held digital electronic manometer. The vacuum applied was 0.45 Bar and the permeation index was taken as the time elapsed for the decay of the applied pressure from 0.45 Bar to 0.55 Bar.

Initial Surface Absorption Test (ISAT)

This test is described in BS 1881 Part 5 (British Standards Institute 1970). A cap is sealed to the concrete surface. The system is filled with water and the rate of flow into the surface is measured by observing the movement of a meniscus in a capillary tube. The Initial Surface Absorption (ISA) is defined as the rate of flow at stated intervals after the start of the test. ISA_{10} is the flow after ten minutes in $m^3/m^2/s$.

Covercrete Absorption Test (CAT)

In an effort to improve the reliability and the repeatability of the Figg water permeability test (Figg, 1973), Dhir et al (1987) developed the Covercrete Absorption Test. The water flow measurement system from the ISAT test is used. The test assesses the absorption characteristics over the full depth of a 50 mm hole drilled in the cover concrete. A hole of 13 mm diameter x 50 mm deep was drilled on one of the surfaces (not the as cast surface) and a gasketted cap with an internal diameter of 13 mm was clamped to the test specimen with the end of the inlet tubing about 2 mm above the bottom of the hole (Figure 2). De-ionized, de-aired water was fed into the hole from a reservoir, then through the outlet of the cap into a capillary tube. The water pressure was maintained at 200 mm head above the centre of the hole. The covercrete absorption index CAT_{10} is defined as the volume of water absorbed by concrete unit area per second ten minutes after starting the test.

Air Permeability of Near Surface (APNS)

This test was developed by the present authors and the details have been published (Dhir et al. 1995). The test makes use of the cap from the ISAT test but measures vacuum decay in a similar manner to the Figg test. The APNS index is defined as the time in seconds for the pressure in the cap to rise from 0.01 Bar to 0.9 Bar.

MODELLING OF THE TESTS

General Model

The modelling of all four tests is based on the Darcy equation for pressure driven flow (Illston 1994):

$$F = \frac{KA}{E}\frac{dp}{dx} \qquad (1)$$

where :

F is the flow rate in m^3/s

K is the intrinsic permeability in m^2

E is the viscosity of the water in Pa s

p is the pressure in Pa at a distance x m from the high pressure reservoir.

A is the area in m^2 across which the water is flowing.

For the vacuum decay tests the applied pressure is atmospheric and for the water absorption tests it is capillary suction.

The vacuum decay tests.

In these tests the permeating fluid is compressible and the observed flux F in m^3/s will therefore change with pressure. The flow is therefore best expressed as molecular flow where N is the total flux in $mol/m^2/s$ and dn/dt is the flow rate of the gas (mol/s). Both N and dn/dt are approximately constant across the sample (assuming a steady state within it).

Equation (1) therefore becomes:

$$N = \frac{1}{A}\frac{dn}{dt} = \frac{Fp}{A}RT = -\frac{Kp}{ERT}\frac{dp}{dx} \qquad (2)$$

where

R is the gas constant (8.31 J/mol/°K)

and

T is the temperature in °K

t is the time from the start of the test in s

note that this equation and all others derived from it differ from the incorrect analysis given by Dhir (1995).

The change of pressure in the vacuum chamber will be given by

$$\frac{dP}{dt} = \frac{dn}{dt}\frac{RT}{V} \qquad (3)$$

Where V is the evacuated volume

and

P is the pressure in it

In order to apply these equations it is now assumed that the gas is flowing into the vacuum from a region a distance X metres away where there is a large reservoir of gas at atmospheric pressure.

The APNS test.

In this test the flow is approximately one-dimensional out of the concrete towards the vacuum. The area A is therefore constant. Integrating equation (1) across the sample gives:

$$\frac{dn}{dt} = \frac{KA(P_{atm}^2 - P^2)}{2XERT} \qquad (4)$$

Combining this with equation (3) gives:

$$V\frac{dp}{dt} = \frac{KA(P_{atm}^2 - P^2)}{2XE} \qquad (5)$$

The integral of this expression for has been given by Harris et al. (1993) and gives:

$$\frac{(P + P_{atm})(P_i - P_{atm})}{(P - P_{atm})(P_i + P_{atm})} = \exp\left[\frac{KAP_{atm}t}{EXV}\right] \qquad (6)$$

where:

P_i is the initial vacuum.

and

P_{atm} is atmospheric pressure.

The APNS index is the value of t when P reaches 90kPa from an initial P_i = 1kPa

The Figg test.

The Figg test has a cylindrical geometry thus:

$$A = 2\pi x L$$
$$and$$
$$V = \pi x_0^2 L \qquad (7)$$

where:

x is the radius at which the flow is being considered.

L is the length of the evacuated volume in m.

x_0 is its radius.

Following through the integration as for the APNS test gives:

$$\frac{(P + P_{atm})(P_i - P_{atm})}{(P - P_{atm})(P_i + P_{atm})} = \exp\left[\frac{2KP_{atm}t}{Ex_0^2 \ln(X/x_0)}\right] \qquad (8)$$

The Figg permeation index is the value of t when P reaches 55kPa from an initial P_i = 45kPa.

The Water flow tests

The analysis of these tests has been given by the authors (Claisse et al.1997). The flow for the ISAT test is:

$$F = A\left(\frac{Ks\alpha}{rE}\right)^{1/2} t^{-1/2} \qquad (9)$$

where:

s is the surface tension of water in N/m

r is the radius of the pores in the concrete

and

α is the porosity

The absorption ISA_{10} is F/A when t=600.

For the CAT test the flow is expressed indirectly as:

$$t = \frac{\gamma}{\delta} e^{\delta/F} \left(\frac{\delta}{F} - 1 \right) + \frac{\gamma}{\delta} \qquad (10)$$

where:

$$\delta = \frac{8\pi LKs}{rE}$$

$$and$$

$$\gamma = \alpha \pi L x_0^2$$

The covercrete absorption CAT_{10} is F/A when t = 600.

PROCESS OF VACUUM DRYING

The process operates by removing moisture under vacuum from the surface of concrete, with equilibrium being defined by a suitable humidity indicator. A Full description of the method and its application to ISAT is detailed elsewhere (Dhir et al.1993). It was found that vacuum up to 10 mbar is suitable for drying in a reasonable time period, and 3 g of silica gel is sufficient as a drying indicator.

Pilot trials were conducted in order to test the vacuum system prior to CAT and Figg. The vacuum technique was used for preconditioning test concrete (100 mm cubes) by drilling holes 13 mm diameter by 50 mm depth and subjecting the test specimens to different moisture conditions. The vacuum was applied as described by Dhir et al (1993) and the preconditioned concrete specimens were tested using both CAT and Figg tests immediately after the silica gel colour turned blue. The results obtained from both CAT and Figg test were not reproducible (i.e. the vacuum preconditioning method failed to give similar results regardless the moisture history of the test concrete).

Reproducibility was improved by applying the vacuum directly to the hypodermic needle prior to the Figg test and to the CAT cap prior to CAT. This is probably because of the concentration of vacuum on the immediate test area compared to the larger area under the ISAT cap and subsequent reduction of the leakage around the cap. Splitting cubes after preconditioning by vacuum showed that the drying front shape (see Figure 3) is similar to the wetting front shape obtained by applying the absorption test (Claisse et al.1997). Therefore, preconditioning the test area using CAT cap or the hypodermic needle of the Figg test leads to a drying of the concrete volume which will be tested by the specific permeation test.

APPLICATION OF THE VACUUM SYSTEM PRIOR TO PERMEATION TESTS

Further Development of the Test Apparatus

A separate perspex silica gel chamber was developed for placing in the vacuum line in order to monitor the progress of drying since it was not possible to use the same arrangement as in the larger ISAT cap (see Figure 4 (a)). Figure 4 (b) shows the application of the vacuum through a hypodermic needle to precondition concrete prior to Figg test.

Preparation of Test Samples

Two concrete mixes with mean strengths of 35 and 60 N/mm^2 were used (mix proportions are detailed by Dhir et al.1993). The test specimens, 100 mm cubes, were cast and kept under wet hessian for 1 day before demoulding. Subsequently, two curing conditions were used: water curing at 20°C; and air curing at 200°C, 55% RH, until testing at 28 days.

Experimental Design

An effective preconditioning method should produce similar permeation results from similar samples (i.e. samples with equal mix proportions and curing regimes) regardless of the initial moisture content of these samples. The test program was therefore carried out on sets of samples from one mix which had been cured in an identical manner and then brought to different moisture contents before preconditioning. The effectiveness of the vacuum drying technique in giving similar results from each set was then compared with BS 1881 (1970) drying methods (2 days drying in the laboratory and drying in oven at 105°C to constant weight) using the variance ratio test known as F test. The methods used to bring samples to different moisture contents were:

1. Vacuum saturation for 2 hours at 10-15 mbar (typical weight gain from air curing = 2%).
2. Six hours in water (typical weight gain from air curing = 1%).
3. Drying in laboratory air for 28 days.

For each grade, curing condition, moisture content and drying method, two samples were tested giving a total of 72 samples for each test.

RESULTS AND DISCUSSION

The vacuum drying.

The results for CAT and Figg test are shown in Tables 2, 3 and Figures 5, 6. The coefficient of variation (V% = the standard deviation divided by the mean) has been calculated from the CAT_{10} and permeation index results from each moisture condition, i.e. a total of 6 samples in each case. The statistical F test is used to compare the variability in the set preconditioned by vacuum with that in the sets preconditioned in the oven or in the laboratory for 2 days. Because the means of the sets were not equal, the coefficient of variation is used to calculate the variance ratio (F ratio) (Kennedy and Neville 1986). The two sided F test was applied on the null hypothesis that the variation in results caused by the different moisture contents was the same for the different preconditioning methods. The critical value for the variance ratio is called the F statistic. The F statistic for 95 % confidence limits is 7.15 (both degrees of freedom being 5).

The F ratios are shown in Tables 2 and 3 for each of the four mix/curing combinations. It can be seen that the coefficients of variation of the vacuum dried samples were significantly less than those for the two day room dried samples except for water cured concrete (60 N/mm^2), i.e. the null hypothesis can not be rejected for concrete of grade 60 (cured in water). The sensitivity of the tests to changes in concrete decreases with the increase of concrete grade.

Figures 5 and 6 show that the oven drying method produces highest CAT and lowest Figg values. The oven drying method gave lowest coefficient of variations for CAT. However, coefficient of variations for Figg values obtained after oven drying were comparable to those obtained after vacuum preconditioning. It is clear from Figures 5 and 6 that the error bars, represent the mean ± standard deviation, are overlapped for water cured concrete (grade 35) and air cured concrete (grade 60) regardless the preconditioning method used.

THE CHOICE OF TEST FOR PRACTICAL APPLICATIONS.

When deciding which test to use on a given structure the most important consideration may be the existence of local knowledge or standards and is not considered here. The damage to the structure caused by the tests is on a similar scale for all four tests since the two which do not involve drilling a hole result in an unsightly grease deposit on the surface which is difficult to remove. The amount of work involved in carrying out each of the tests is also similar. The following discussion therefore only considers the ability of the tests to determine the potential durability.

While all of the tests measure permeability it may be seen that two measure this for gas and two for water. Bamforth (1987) has published a very comprehensive discussion of the effect of gas slippage and gives a graph to correct for it at different pressures. In Table 4 two different concretes, A and B are considered with water permeabilities of 10^{-17} and 10^{-18} m^2. These permeabilities are typical for grade 35 and 60 concretes (Bamforth 1987). The corresponding gas permeabilities, the calculated results for the four tests for each concrete and the average measured coefficient of variation for the tests on the concretes reported in this paper (using vacuum drying) are given. The variation for the ISAT was obtained from earlier work (Dhir et al.1993)

The values used for the calculations in Table 4 are:

R	Gas Constant	8.31 J/mol/°K
T	Temperature	293 °K
E	Viscosity of water	10^{-3} Pa s
s	Surface tension of water	0.073 N/m
A	Area under ISAT test cap	5.8×10^{-3} m^2
V	Volume under ISAT test cap	2.9×10^{-5} m^3
L	Depth of drilled hole	50mm
x_0	Radius of drilled hole	6.5mm
P_{atm}	Atmospheric pressure	100 KPa
P_{in}	Initial Vacuum	45kPa for Figg test and 1kPa for APNS test
P	Final pressure	55kPa for Figg test and 90kPa for APNS test
α	Porosity	7%
r	radius of largest pores	0.6 μm (Claisse et al. 1997)

The unknown constant is X the distance over which the pressure drop occurs in the gas tests. Dhir et al (1995) suggest that no value of X is used and that K/X is used as a measure of permeability rather than K. This approach cannot be used for the Figg test because the cylindrical geometry gives a logarithmic relationship in equation (8). For the present discussion the value is not important and a realistic estimate of 10mm has been used. Harris (1993) has published an extensive investigation which used computer modelling to avoid the necessity to use a simplified "permeation block" and concluded that for low porosity concretes, such as those used in the work reported here, the effect of the approximation is not substantial.

The table shows that the derived equations give realistic values for the different test results.

The conclusion from the table is that the water tests, in particular the CAT test should give better distinction between different concrete qualities because of the higher proportional change in the measured value for a given change in concrete permeability. The coefficient of variation may also be seen to be lower for the water tests (data is not currently available for the APNS test). It must be observed, however, that the tests measure different properties in that the water tests measure capillary suction as well as permeability. If possible a site test programme should therefore use both tests. These results do not indicate a very clear preference for either surface or drilled hole tests. It may be argued that the drilled hole tests will be less affected by surface effects or contamination but the surface tests measure the ingress of fluids into a structure more realistically.

CONCLUSIONS

1. The vacuum technique can be applied successfully prior to CAT and Figg test with slight modification to the apparatus in order to give reproducible results.

2. Analytical models may be used to calculate permeabilities from these tests.

3. For practical use the results indicate that the water tests give better results than the gas tests. No clear advantage of either drilled hole or surface tests was observed.

APPENDIX 1

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APPENDIX II NOTATION

The following symbols are used in this paper:

A = Area across which the water is flowing (m^2).

E = Viscosity (Pa s)

F = Flow rate (m^3/s)

K = Intrinsic permeability (m^2)

L = Depth of drilled hole (mm)

N = Total flux $mol/m^2/s$

n = number of mols

p = Pressure at a distance x m from the high pressure reservoir (Pa).

P = Final pressure (Pa)

P_{atm} = Atmospheric pressure (Pa)

P_{in} = Initial Vacuum (Pa)

R = Gas Constant (J/mol/°K)

r = Radius of largest pores (m)

s = Surface tension (N/m)

t Time

T = Temperature (°K)

V% = Coefficient of variation %

V = Volume (m^3)

X = Distance across permeation block (m)

x = Distance (m)

x_0 = Radius of drilled hole (m)

α = Porosity

$\gamma = \alpha \pi L x_0^2$

$\delta = (8\pi LKs)/rE$

Table 1. Summary of Test Methods

	Test Geometry	
Test Procedure	Surface	Drilled Hole
Apply vacuum and measure time for decay	Air Permeability of Near-Surface (APNS)	Figg air permeation index
Apply water and measure flow into concrete	Initial Surface Absorption Test (ISAT)	Covercrete Absorption test (CAT)

Table 2 Figg test results for different preconditioning methods

CONCRETE GRADE: N/mm^2	CURING	PRE-CONDITIONING	MEAN Index, s	V% of Index	F-STATISTIC
35	Air	Vacuum dry	8	14.0	1.0
		2 day air	14	63.0	20.3
		Oven dry	7	12.0	1.4
35	Water	Vacuum dry	61	20.5	1.0
		2 day air	121	60.0	7.2
		Oven dry	38	8.0	6.6
60	Air	Vacuum dry	57	19.0	1.0
		2 day air	112	56.0	10.0
		Oven dry	30	8.4	5.1
60	Water	Vacuum dry	227	23.0	1.0
		2 day air	400	43.0	3.5
		Oven dry	150	9.5	5.9

Table 3 CAT results for different preconditioning methods

CONCRETE GRADE: N/mm^2	CURING	PRE-CONDITIONING	MEAN CAT_{10} 10^{-2}ml/m^2/s	V% of CAT_{10}	F-STATISTIC
35	Air	Vacuum dry	121.4	19.5	1.0
		2 day air	106.5	59.5	9.3
		Oven dry	185.0	12.5	2.4
35	Water	Vacuum dry	58.3	15.0	1.0
		2 day air	38.0	51.0	11.6
		Oven dry	110.0	11.0	1.9
60	Air	Vacuum dry	63.5	12.0	1.0
		2 day air	41.5	39.0	10.6
		Oven dry	115.0	8.0	2.3
60	Water	Vacuum dry	16.0	10.0	1.0
		2 day air	14.0	24.0	5.8
		Oven dry	85.0	5.0	4.0

Table 4. Comparison of Test Methods.

	Water Permeability K m^2	ISAT 10 minute reading ISA_{10} 10^{-2} $ml/m^2/s$	CAT 10 minute reading CAT_{10} 10^{-2} $ml/m^2/s$	Gas Permeability at 0.5 atmospheres absolute K m^2	APNS Permeation index s	Figg Permeation index s
Concrete A	10^{-17}	37	59	2×10^{-16}	7300	120
Concrete B	10^{-18}	12	14	10^{-16}	14600	240
Ratio A/B		3.1	4.2		0.5	0.5
Average V% (vacuum dried)		15.7	14.1		-	19.1

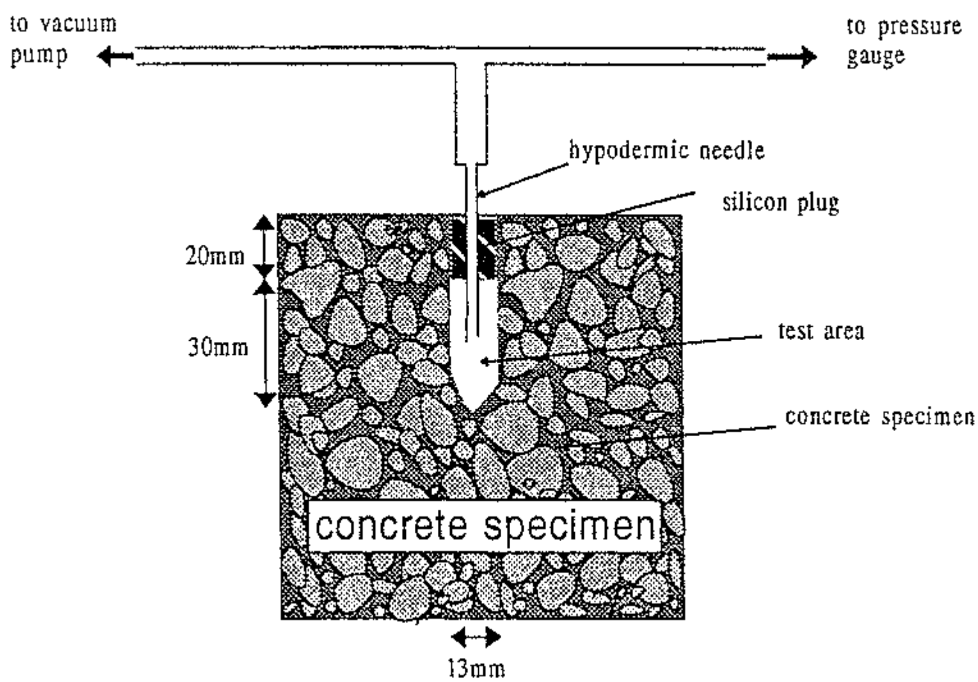

Figure 1 Schematic Arrangement of Figg Test.

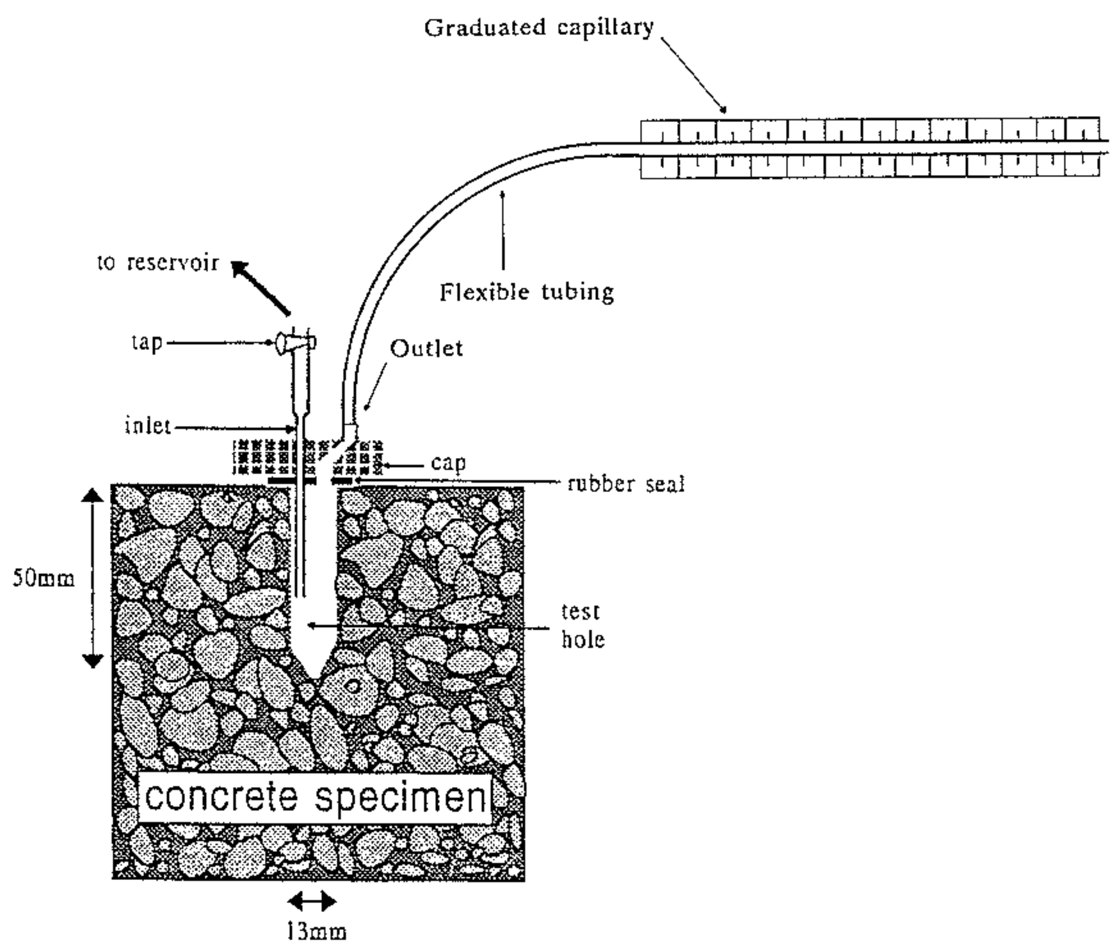

Figure 2. Schematic arrangement of CAT

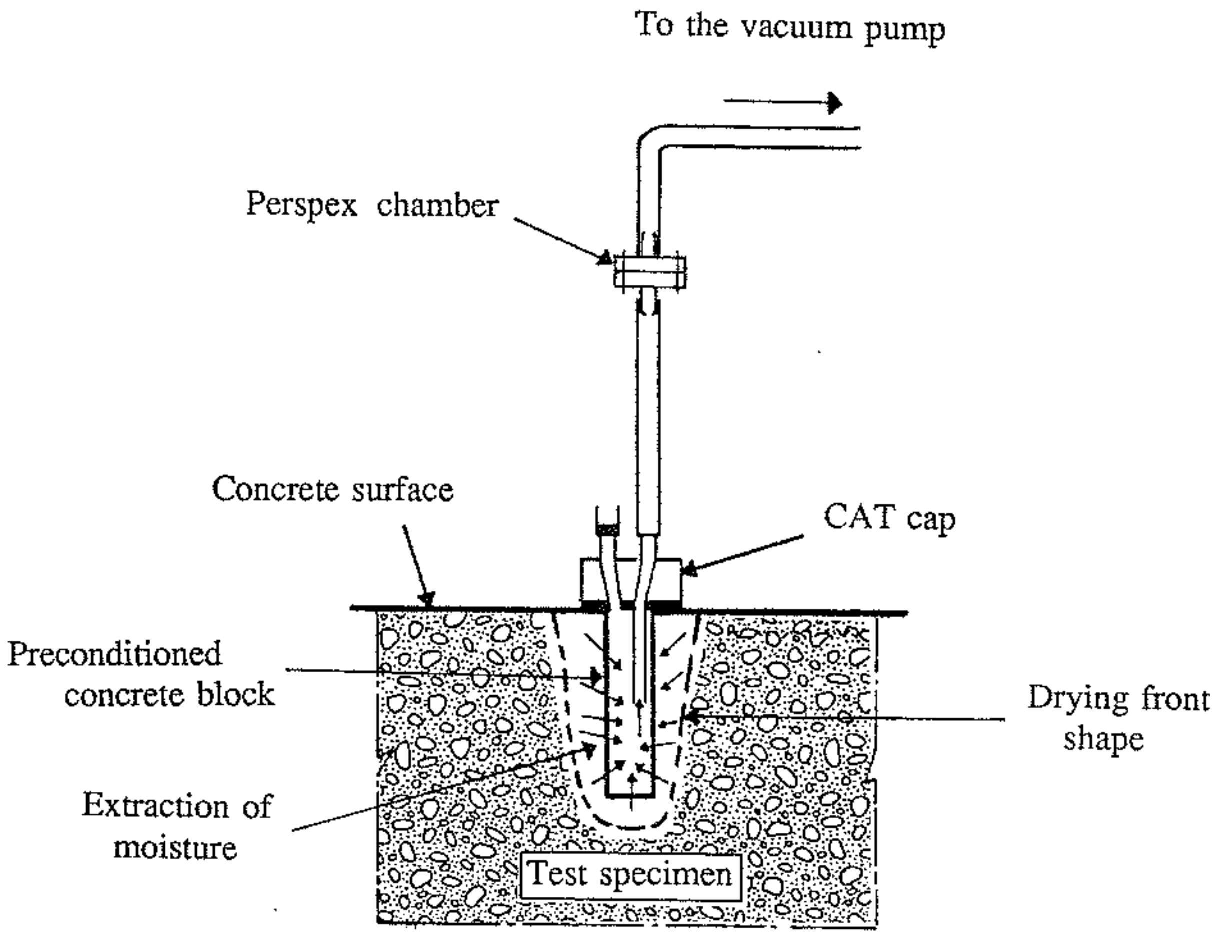

Figure 3 Vacum drying front shape for CAT

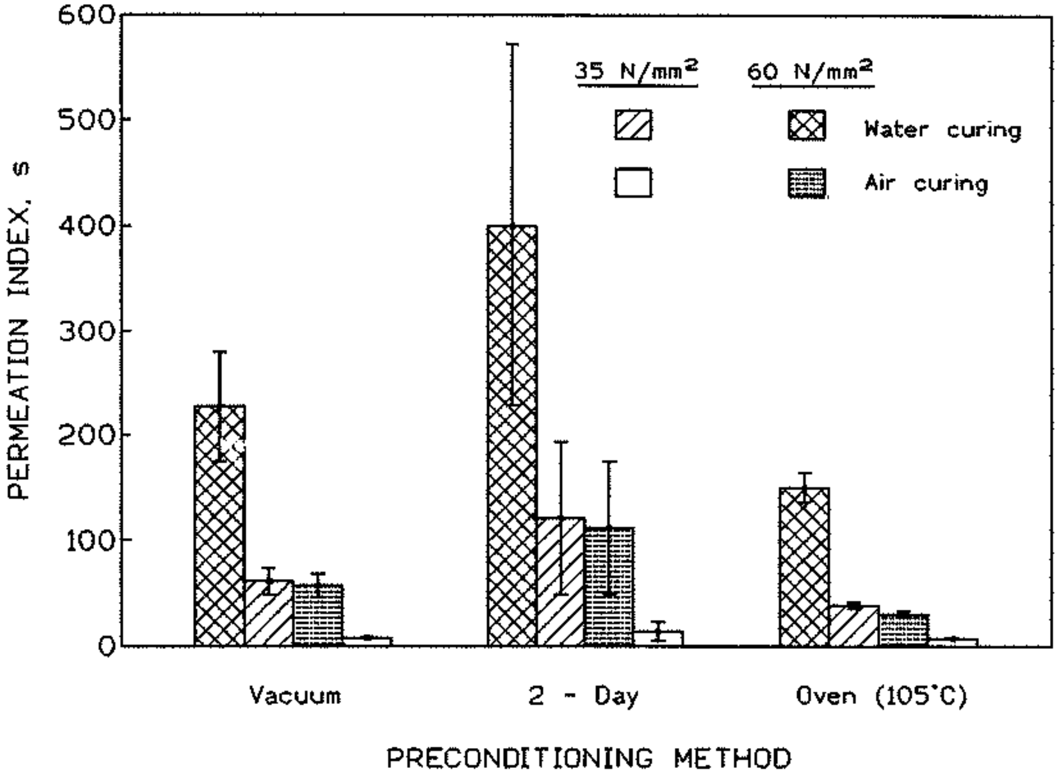

Figure 5 Effect of Preconditioning Method on Figg Results

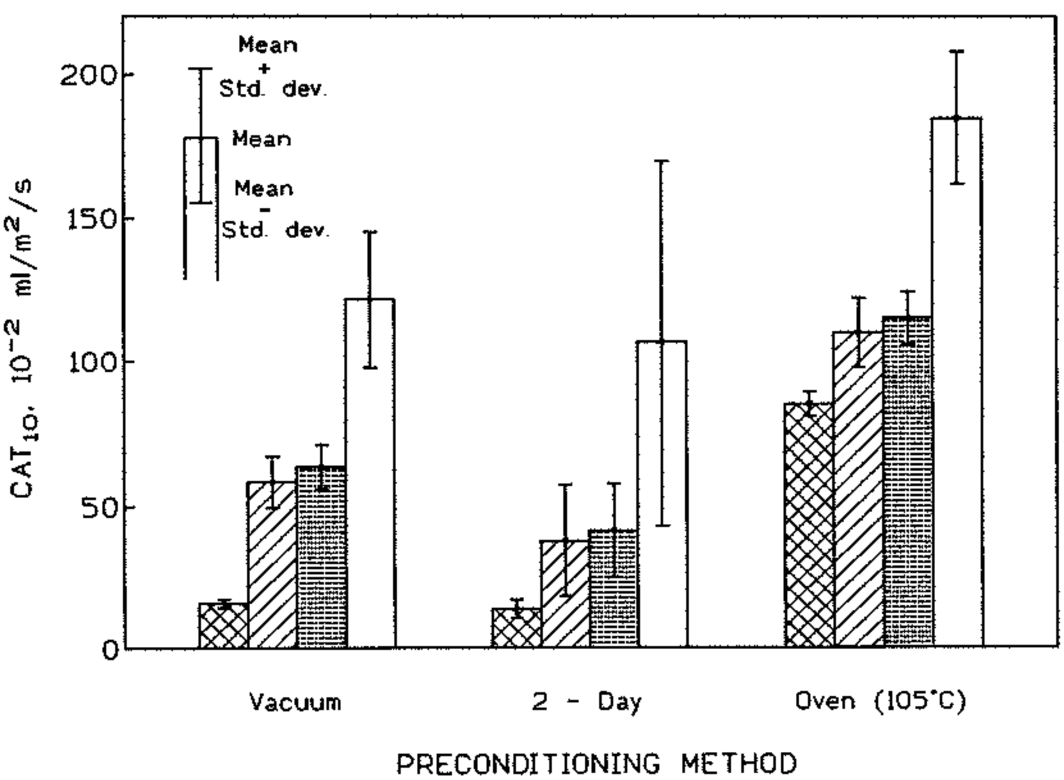

Figure 6 Effect of Preconditioning Method on CAT Results